

# The magnetar model of the superluminous supernova GAIA16apd and the explosion jet feedback mechanism (JFM)

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## ABSTRACT

Under the assumption that jets explode core collapse supernovae in a negative jet feedback mechanism (JFM), I show that rapidly rotating neutron stars are likely to be formed when the explosion is very energetic. Under the assumption that an accretion disk or an accretion belt around the just-formed neutron star launch jets and that the accreted gas spins-up the just-formed neutron star, I derive a crude relation between the energy that is stored in the spinning neutron star and the explosion energy. This relation reads  $(E_{\text{NS-spin}}/E_{\text{exp}}) \approx E_{\text{exp}}/10^{52}$  erg. It shows that within the frame of the JFM explosion model of core collapse supernovae, spinning neutron stars, such as magnetars, might have significant energy in super-energetic explosions. The existence of magnetars, if confirmed, such as in the recent super-energetic supernova GAIA16apd, further supports my call for a paradigm shift from neutrino-driven to jet-driven core-collapse supernova mechanisms.

## 1. INTRODUCTION

The two contesting explosion mechanisms of core collapse supernovae (CCSNe) to utilize the gravitational energy that is released during the formation process of the neutron star (NS; or black hole) are the delayed neutrino mechanism (e.g., Bruenn et al. 2016; Janka et al. 2016; Müller 2016; Burrows et al. 2017; for recent papers), and the jet feedback mechanism (JFM; e.g., Papish et al. 2016; Gilkis et al. 2016, and Soker 2016 for a recent review). The collapse-induced thermonuclear explosion (CITE) mechanism (Burbidge et al. 1957; Kushnir & Katz 2015) is based on nuclear energy, and it requires a large amount of angular momentum (Kushnir 2015a). This implies that an accretion disk is formed around the newly born NS (Gilkis et al. 2016; confirmed by Blum & Kushnir 2016), and jets that are expected to be launched by the accretion disk dwarf the energy of the thermonuclear reactions (Gilkis et al. 2016).

The delayed neutrino mechanism encounters some difficulties and it is not clear whether it can explain even a small fraction of CCSNe (e.g., Papish et al. 2015; Kushnir 2015b). In any case, even the most optimistic studies show that the delayed neutrino mechanism cannot explain CCSN explosion energies of  $E_{\text{exp}} \gtrsim 2 \times 10^{51}$  erg (e.g., Fryer 2006; Fryer et al. 2012; Sukhbold et al. 2016; Sukhbold & Woosley 2016; by explosion energy I refer to the kinetic energy and the radiated energy of the CCSN). For that, the quest for the powering mechanism of super-energetic SNe (SESNe;  $E_{\text{exp}} \gtrsim 10^{52}$  erg) is a hot topic (e.g., Gal-Yam 2012; Moriya et al. 2015; Wang et al. 2016; Arcavi et al. 2016; Sorokina et al. 2016).

Many studies attribute the extra energy of very luminous CCSNe, termed superluminous SNe, or of SESNe to magnetars, i.e., strongly-magnetized, rapidly-rotating NS (e.g., Kasen & Bildsten 2010; Woosley 2010; Metzger et al. 2015). In a recent paper (Soker 2016) I show that under reasonable assumptions the formation process of a magnetar will be accompanied by the launching of energetic jets, and that the jets

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can carry an amount of energy that surpasses the energy that is stored in the newly born magnetar. This raises the possibility that some superluminous CCSNe are powered by late jets as part of the JFM (e.g., Gilkis et al. 2016), rather than by a magnetar.

A recent superluminous CCSN for which the magnetar model was applied is GAIA16apd. Yan et al. (2017) estimate the ejected mass of GAIA16apd to be  $M_{\text{ej}} \simeq 12M_{\odot}$ , and for an opacity of  $\kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}$  derived an explosion energy of  $E_{\text{exp}} > 2 \times 10^{52} \text{ erg}$ . Nicholl et al. (2017) present a magnetar explanation for the superluminosity. In their model the ejected mass is  $M_{\text{ej}} = 4(0.2 \text{ cm}^2 \text{ g}^{-1}/\kappa)M_{\odot}$ , the spin period of the pulsar is  $P = 2 \text{ ms}$ , and its magnetic field is  $B = 2 \times 10^{14} \text{ G}$ . Kangas et al. (2016) has a consistent magnetar model, within the uncertainties, with  $M_{\text{ej}} = 7(0.2 \text{ cm}^2 \text{ g}^{-1}/\kappa)M_{\odot}$ , and explosion energy of  $M_{\text{ej}} = 1 \times 10^{52}(0.2 \text{ cm}^2 \text{ g}^{-1}/\kappa) \text{ erg}$ , and for the magnetar they deduce  $P = 1.9_{-0.2}^{+0.3} \text{ ms}$ , and  $B = 2.1_{-0.2}^{+0.5} \times 10^{14} \text{ G}$ .

Not only such a superluminous CCSN requires a long lasting central engine, such as jets or a magnetar, but the explosion itself most likely is driven by jets. The possibility that jets play a role in the explosion process of massive stars has been mentioned in the literature over the years. Three examples, among many others, are the recent paper by Mauerhan et al. (2017) who discuss the axisymmetrical explosion of SN 2013EJ, the polarimetric observations of SN 2015bn that indicate an elongated morphology (Inserra et al. 2016), and the presence of jets in CCSN remnants (e.g., Lopez et al. 2014; Milisavljevic et al. 2013). As well, many studied simulated jets in CCSNe (e.g., Bromberg & Tchekhovskoy 2016). However, the majority of these papers refer to jets only in rare CCSNe and/or as an additional component to the explosion mechanism that was assumed to be driven by neutrinos. I take the view that in all these cases, and in the majority of (or even all) regular CCSNe, jets explode the star rather than neutrinos, and that the jets operate in a negative feedback mechanism (see Soker 2016 for a review). For example, under this view the association of gamma ray bursts with type Ic supernovae (e.g., Cano et al. 2016) is a result of the explosion being driven by jets.

In the present study I explore the implications of magnetar formation in the context of the explosion JFM. When pre-collapse rapidly rotating cores collapse, they form an accretion disk around the newly born NS or black hole (e.g., Gilkis 2017), and jets are likely to be launched (e.g., Nishimura et al. 2015). I take this into account in evaluating the connection between the newly born magnetar and the JFM. I do not claim that magnetar is the only possible powering mechanism of this superluminous CCSN, as jets might also account for extended operation of the central engine. I simply reveal the implications of the existence of a magnetar.

## 2. ANGULAR MOMENTUM AND ENERGY

Nicholl et al. (2017) use the magnetar model presented by Inserra et al. (2013) who took the angle between the magnetic axis and spin axis to be  $45^\circ$ . If the angle is smaller, then a more rapid rotation is required to have the same cooling time. So one should bear in mind the uncertainties in the values of spin period and energy of the magnetar model.

As discussed in section 1, I think that the JFM is the only viable model to account for the explosion of GAIA16apd. I now discuss the implication of accretion of mass and angular momentum onto the just-formed (newly born) NS. I assume that after the shock bounces from the just-formed NS, the NS does not rotate rapidly. I consider then that a mass  $M_{\text{acc}}$  is accreted onto the newly born NS, and launches jets. The accreted gas can form an accretion disk or an accretion belt (Schreier & Soker 2016).

The energy that is accreted through the accretion disk or accretion belt and transferred to the jets is taken to be

$$E_{\text{exp}} \simeq E_{\text{jets}} = \xi \frac{GM_{\text{NS}} M_{\text{acc}}}{2R_{\text{NS}}} = 2.6 \times 10^{52} \xi \left( \frac{M_{\text{NS}}}{1.5M_{\odot}} \right) \left( \frac{R_{\text{NS}}}{15 \text{ km}} \right)^{-1} \left( \frac{M_{\text{acc}}}{0.2M_{\odot}} \right) \text{ erg}. \quad (1)$$

Strictly speaking, the binding energy of the ejected mass should be removed from the energy in the jets to obtain the explosion energy. But for the discussed type of superluminous CCSNe the explosion energy is much larger than the binding energy.

I take the specific angular momentum of the accreted mass,  $J_{\text{acc}}$ , to be about equal to that of the critical value (about Keplerian orbit) on the surface of the NS. I further assume that this is about the final angular momentum of the NS,  $J_{\text{NS}} = \beta J_{\text{acc}}$ . This is a crude estimate for the following processes. (1) The mass might be accreted onto a larger radius than  $R_{\text{NS}}$ , hence with a larger angular momentum, before the NS makes the contraction to its final radius. (2) The final angular momentum of the NS can be larger if the just-formed NS has initial angular momentum. (3) The final angular momentum of the NS can be smaller if different segments of the accreted mass have different directions of angular momentum. This is the expectation in the jittering-jets model. Despite the crude derivation, I think that it does present the correct trend, and it is adequate for the derivation to follow.

Under the above assumption, the angular momentum of the NS is

$$J_{\text{NS}} = \beta J_{\text{acc}} \simeq \beta M_{\text{acc}} (GM_{\text{NS}} R_{\text{NS}})^{1/2}. \quad (2)$$

The angular momentum of the spinning NS is  $J_{\text{NS}} = I_{\text{NS}} \omega$ , where  $\omega$  is the angular velocity of the NS, and the moment of inertia of a NS is  $I = \eta M_{\text{NS}} R_{\text{NS}}^2$  with  $\eta \simeq 0.3$  (Worley et al. 2008). From equation (2) one can find the ratio of the angular velocity to the critical (maximum) value

$$\frac{\omega}{\omega_c} \simeq \frac{\beta M_{\text{acc}}}{\eta M_{\text{NS}}} = 0.44 \beta \left( \frac{M_{\text{acc}}}{0.2M_{\odot}} \right) \left( \frac{M_{\text{NS}}}{1.5M_{\odot}} \right)^{-1} \left( \frac{\eta}{0.3} \right)^{-1}. \quad (3)$$

Under the above assumption on the final angular momentum of the NS, the ratio of the energy of the spinning NS,  $E_{\text{NS,spin}} = (1/2)I_{\text{NS}}\omega^2$ , to the explosion energy, which is about the energy carried by the jets, is

$$\frac{E_{\text{NS,spin}}}{E_{\text{exp}}} \simeq \frac{\beta^2}{\eta \xi} \frac{M_{\text{acc}}}{M_{\text{NS}}}, \quad (4)$$

where equation (1) has been used for the explosion energy and equation (3) for the angular velocity. A more transparent expression for the present goals can be obtained if equation (1) is used to replace the accreted mass by the explosion energy

$$\frac{E_{\text{NS-spin}}}{E_{\text{exp}}} \simeq \frac{2\beta^2}{\eta \xi^2} \frac{R_{\text{NS}}}{GM_{\text{NS}}^2} E_{\text{exp}} \simeq 0.7 \beta^2 \left( \frac{\eta}{0.3} \right)^{-1} \left( \frac{\xi}{0.5} \right)^{-2} \left( \frac{M_{\text{NS}}}{1.5M_{\odot}} \right)^{-2} \left( \frac{R_{\text{NS}}}{15 \text{ km}} \right) \left( \frac{E_{\text{exp}}}{10^{52} \text{ erg}} \right). \quad (5)$$

The meaning of this ratio is that in the JFM for exploding massive stars, the energy stored in the spinning NS can be expected to be significant in SESNe, but not in regular CCSNe.

The ratio of spinning energy to the explosion energy depends stronger even on the explosion energy. For slowly pre-collapse rotating core, the specific angular momentum of the accreted mass is more stochastic (the jittering jets explosion mechanism), and the final angular momentum of the NS is lower, e.g.,  $\beta < 1$ , and even  $\beta \ll 1$ , in equation (2). This is a case of typical CCSNe. When the pre-collapse core is rapidly

rotating, the JFM is less efficient, and the explosion energy is expected to be larger (Gilkis et al. 2016). In the case of a rapidly rotating pre-collapse core, the just-formed NS is expected to have angular momentum in the same sense as the accreted mass that forms jets, and hence the value of  $\beta$  can be somewhat larger than 1.

The main conclusion from the simple derivation presented in this section is that the JFM for exploding CCSNe can account for rapidly spinning NS in the case of energetic explosions, i.e., for superluminous CCSNe that are not powered by collision of the ejecta with the circum-stellar matter, and for SESNe. In other words, a magnetar is a possible outcome of the JFM explosion of SESNe.

### 3. SUMMARY

Under the assumption that jets explode super-energetic supernovae (SESNe) in a negative jet feedback mechanism (JFM), I derived a crude relation between the explosion energy and the energy of the rotating NS at the end of the accretion phase, i.e., few seconds after core-collapse. This relation that is presented in equation (5), shows that within the frame of the JFM explosion model of CCSNe, spinning NS, such as magnetars, can have significant energy only in super-energetic explosions (SESNe).

In other words, a rapidly rotating NS is a natural outcome of the JFM in the case of energetic explosions. In that sense, the existence of magnetars, if confirmed, such as in the recent SESN GAIA16apd, supports the JFM explosion model of CCSNe. I do note that it is possible that some superluminous CCSNe are powered by long-lasting jets rather than by a magnetar (e.g., Gilkis et al. 2016).

The JFM model for exploding CCSNe is not yet in a stage of a developed model, as there are no simulations that demonstrate its operation from core collapse to explosion in different cases. At this stage, different observations and theoretical arguments are accumulated in small increments to support its potential as a viable mechanism for exploding most CCSNe. The present paper is another step forward in supporting the JFM as the major process to explode massive star.

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